The potential of spectrodirectional CHRIS/PROBA Data for biochemistry estimation

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Abstract: Sun and sensor geometry cause directional effects in remotely sensed reflectance data which can influence the estimation of biophysical and biochemical variables. Previous studies have indicated that bidirectional measurements contain added information with which the accuracy of derived plant structural parameters can be increased. Because accurate biochemistry mapping is linked to vegetation structure, estimates of nitrogen concentration (CN) and water content (CW) might be indirectly improved with multiangular information. We analyzed data of the spaceborne ESA-mission CHRIS on-board PROBA-1, which provides hyperspectral and directional data. The images were acquired in July 2006 over a forest study site in Switzerland. From each of the five CHRIS images (five different viewing zenith angles) we extracted 60 crown spectra, which correspond to field-sampled trees. Then we developed four-term models by regressing lab-measured CN and CW on two datasets either consisting of original reflectance values (SPEC) or continuum-removed data (BNC). The wavebands used in the regression models were determined with a subset selection algorithm. For the data of all view angle combinations particular models were generated, in total 31 equations were evaluated per spectral dataset by comparing the coefficients of determination (R2) and cross-validated root mean square errors. The results showed that directional information contained in multiangular data improved regression models for CN and CW estimation and lowered RMS errors. Considerable contribution can be achieved with data of a second and third viewing zenith angle. Monodirectional models developed on data of backward scattering angles performed in general better than models based on forward scattering data. Multidirectional models based on combinations of off-nadir data performed best for CN but not for CW. These findings support the potential of multiangular Earth observations for ecological monitoring and modeling studies.

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THE POTENTIAL OF SPECTRODIRECTIONAL CHRIS/PROBA DATA FOR BIOCHEMISTRY ESTIMATION

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ABSTRACT

Sun and sensor geometry cause directional effects in remotely sensed reflectance data which can influence the estimation of biophysical and biochemical variables. Previous studies have indicated that bidirectional measurements contain added information with which the accuracy of derived plant structural parameters can be increased. Because accurate biochemistry mapping is linked to vegetation structure, estimates of nitrogen concentration (C_N) and water content (C_W) might be indirectly improved with multiangular information. We analyzed data of the spaceborne ESA-mission CHRIS on-board PROBA-1, which provides hyperspectral and directional data. The images were acquired in July 2006 over a forest study site in Switzerland. From each of the five CHRIS images (five different viewing zenith angles) we extracted 60 crown spectra, which correspond to field-sampled trees. Then we developed four-term models by regressing lab-measured C_N and C_W on two datasets either consisting of original reflectance values (SPEC) or continuum-removed data (BNC). The wavebands used in the regression models were determined with a subset selection algorithm. For the data of all view angle combinations particular models were generated, in total 31 equations were evaluated per spectral dataset by comparing the coefficients of determination (R^2) and cross-validated root mean square errors. The results showed that directional information contained in multiangular data improved regression models for C_N and C_W estimation and lowered RMS errors. Considerable contribution can be achieved with data of a second and third viewing zenith angle. Monodirectional models developed on data of backward scattering angles performed in general better than models based on forward scattering data. Multidirectional models based on combinations of off-nadir data performed best for C_N but not for C_W. These findings support the potential of multiangular Earth observations for ecological monitoring and modeling studies.

1. INTRODUCTION

Many internal and external factors affect forest canopy reflectance: the canopy reflectance distribution is primarily a function of leaf optical properties, canopy architecture, soil and understory, atmospheric conditions, solar illumination and sensor observation geometry. Biochemical variables, such as water content can be estimated from spectral remote sensing information, but the influence of canopy structure can lead to inaccurate estimates of these variables. This is because canopy structure significantly influences the visible and near-infrared canopy reflectance. To improve biochemical estimates, an accurate retrieval of canopy structural properties is thus fundamental. It has been shown that leaf area index (LAI) and leaf orientation have a strong effect on the expression of leaf optical properties, and thus the biochemistry of foliar material, at canopy scales [1]. For canopies with small LAI, foliar biochemistry is generally underrepresented. In particular the NIR region, which exhibits the strongest multiple-scattering in green foliage canopies has the best potential for enhancement of the leaf-level signal [1]. Previous studies have shown that estimates of structural properties can be achieved with multi-directional information in higher accuracy that spectral information alone cannot provide [2-6]. The complementation of the spectral with directional information can therefore lead to improved biochemical estimates.

So far, there has been little discussion about using directional information to assess plant biochemical components. The objective of this study was to investigate if directional data lead to improved estimates of C_N and C_W by evaluating regression models generated on data of all possible combinations of CHRIS viewing zenith angles. We explored a) if directional information is still present after continuum removal and normalization have been applied to reflectance values and b) if certain sensor viewing angles or combinations thereof emerge to be beneficial for estimating C_N and C_W.

2. MATERIALS AND METHODS

2.1. Study Site and Field Data

The field data collection was conducted in July 2004 in a mixed forest located in the Swiss Midlands (7°53' E, 47°16' N) at an altitude of about 400–600 meters above see level. The forest stand is composed of a mixture of coniferous and broadleaf species. At the study site we

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determined 15 subplots where field sampling took place. At each subplot 3–10 trees were chosen for foliar sampling as well as structural and positional tree measurements. The species types of these trees were selected more or less according to their proportion in the forest. In total, we sampled data from 60 trees, belonging to nine different species and two plant functional groups. Thirty-tree were counted to the coniferous (evergreen) and 27 to broadleaf (deciduous) functional group.

In order to determine biochemical leaf properties in the laboratory, for each appointed tree, a tree climber sawed off three sunlit canopy branches from which we collected in total 15 leaves from all selected deciduous trees and 40–50 needles from the first three needle years from all needle-leaved trees. For each tree the collected leaf material was pooled, sealed in bags and stored in cool environment for transportation. Tree crown dimensions were assessed with a Hypsometer. The mean (±SE) radius of a broadleaf and a needle-leaf tree crown were found to be 4.1 (±1.3) m and 3.2 (± 0.8) m, respectively [7]. Leaf area index (LAI) was determined with hemispherical photography and ranged from 2.7 to 4.7 [8].

In order to geo-locate the field-sampled tree crowns later in remotely sensed images, the trunk position of each tree was measured during the field campaign with a Trimble GeoXT GPS receiver. The GPS horizontal precision among all trees ranged from 1.4 to 5.0 m with a mean value of 2.5 m [9]. CHRIS data acquisition occurred three years after field data collection but during the same phenological period (July). We assumed a stable C_N and C_W level during July [10] and only small inter-annual variability [11] due to similar climatic conditions in the years of data sampling.

In the laboratory, the projected leaf area, the fresh and dry weight, and the biochemical composition for all 60 collected leaf samples were determined [9]. Table 1 presents the descriptive statistics of the leaf samples.

Table 1. Descriptive statistics of biochemical and structural properties by functional type (BD:broadleaf (deciduous) samples, NE: needle-leaf (evergreen) samples) and data set sizes (n).

Biochemical variables	Func. type	n	Min	Max	Mean	SD
Nitrogen (% dry weight)	BD	27	1.79	2.97	2.26	0.32
	NE	33	1.00	1.59	1.20	0.13
Water (g/cm^2)	BD	21	0.007	0.015	0.010	0.002
	NE	28	0.039	0.092	0.058	0.012

2.2. CHRIS Data Acquisition and Processing

We used the data of the spaceborne ESA-mission CHRIS (Compact High Resolution Imaging Spectrometer) on-board PROBA-1 [12], which provides in mode 5 multiangular data in the range from 447 nm to 1035 nm in 37 bands with a spatial resolution of 18 m. CHRIS supplies five view angles with the nominal fly-by zenith angles (FZA's) at +/-36°, +/-55° and 0° (nadir). The images covered an area of 6.5x13 km and were acquired in July 2006 over the study site.

The actual viewing zenith angles of CHRIS data acquisitions do rarely represent the nominal FZA's due to uncertainties in pointing. As can be seen in Fig. 1, the actual viewing angle for the nadir image was for instance -7.3° in the backward scattering viewing direction.

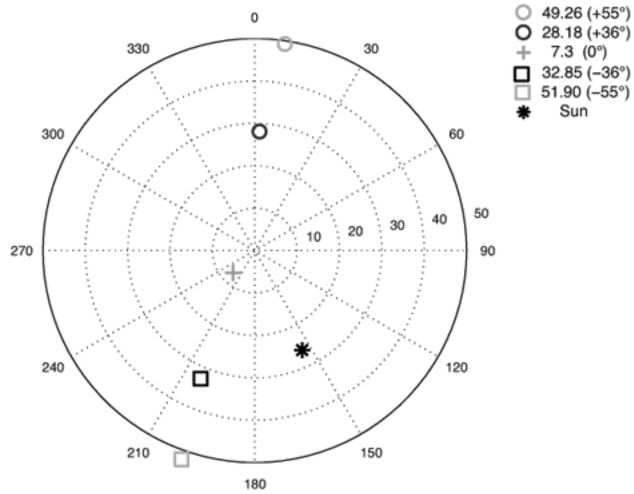


Figure 1. Acquisition geometries and illumination angles for the five CHRIS images acquired on July 1, 2006. The nominal fly-by zenith angles are listed in brackets.

The five CHRIS images were orthorectified and radiometrically corrected [7, 13]. Geometric correction was based on a 3D physical model [14], which is implemented in the commercially available image processing software PCI/OrthoEngine [15] and subsequent atmospheric correction of the CHRIS radiance data was performed using ATCOR-3 [16].

2.3. Tree Crown Spectra Extraction and Processing

After geometric and atmospheric correction, tree spectra of the 60 field-sampled crowns were extracted from each of the five CHRIS images [13]. Figure 2 illustrates the viewing angle dependant spectral signatures extracted from a co-registered pixel representing a single tree crown (Norway spruce).

For further analyses, two datasets were generated. The first consisted of original reflectances (SPEC) of all sampled tree crowns extracted from the five CHRIS images and the second of continuum-removed data (BNC).

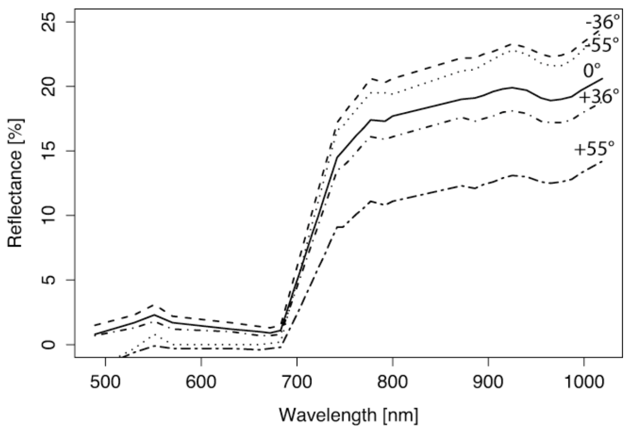


Figure 2. Spectral signatures of Norway spruce from processed CHRIS data of the nominal viewing zenith angles at -/+36°, -/+55° and 0°. Negative viewing zenith angles correspond to backward scattering, positive viewing zenith angles represent forward scattering.

The band depth normalized to the center (BNC) is the ratio of the band depth of each band and the band depth at the band center (Eq. 1):

$$\mathrm{BNC} = \left(1 - \left(R/R_i\right) / 1 - \left(R_c/R_{ic}\right)\right), \tag{1}$$

where R is the reflectance of the sample at the band of interest, R_i is the reflectance of the continuum line at the band of interest, R_c is the reflectance of the sample at the absorption feature center and R_{ic} is the reflectance of the continuum line at the absorption feature center. The band center is the minimum of the continuum-removed absorption feature [17].

Continuum removal is a normalization technique and was developed to enhance the spectral features of interest and to minimize extraneous factors, such as atmospheric absorptions, anisotropic effects or soil background effects [17].

We applied continuum removal for C_N on the absorption feature located between 551 and 755 nm where the leaf water effect is minimal. Studies have shown a strong nitrogen-pigment relationship because the chlorophyll content in foliage is highly correlated with total protein and, hence, total nitrogen content [18-21].

For C_W estimation we were restricted to using the weak liquid water absorption feature at 970 nm [22] owing to the sensor's spectral range regression results solely based on this feature were not satisfactory. The calibration for C_W estimation could be improved by additional utilization of the feature between 551–755 nm.

2.4. Statistical Analyses

Multiple linear regression analysis was applied to fit models between the dependent variables (C_N and C_W) and all possible viewing angle combinations of the two spectral datasets (SPEC, BNC). To limit the number of spectral wavebands used in the regression models, this study employed a statistical variable selection method, namely an enumerative branch-and-bound (B&B) search procedure [23]. Branch-and-bound algorithms are efficient because they avoid exhaustive enumeration by rejecting suboptimal subsets without direct evaluation [24]. As a result, four wavelengths were selected that best explained C_N and C_W. We limited the number of selected wavebands to four to avoid overfitting of the models. All models were tested for significance with the F-test at the 5 % significance level.

An objective of this experiment was to determine whether assessing C_N and C_W could be improved with additional directional information. Therefore, we started fitting models on data extracted from one viewing angle (e.g., nadir). Next, we developed models for all possible combinations of two viewing angles (e.g., nadir and nominal -36°) and continued the analysis with three and four viewing angles to finally introduce the data of all five viewing angles as independent variables. In total, 31 viewing angle combinations were evaluated for each dataset. The findings were evaluated by comparing the mean R^2 for each dataset yielded from models with the same number of viewing angles involved. The contribution of individual angles was evaluated by considering R^2 values for the regressions between field C_N, C_W and the spectral data for all angular combinations. To assess the predictive capability of the models, we used 10-fold cross-validation and calculated root mean square errors (CV-RMSE) and percentage relative errors (% error) for each model [25, 26].

We implemented all analyses within the R statistical package, a free software environment for statistical computing and graphics [27] under the GNU public license.

3. RESULTS

3.1. Contribution of Directional Data

The contribution of angular information to regression models for estimating C_N and C_W is apparent from Fig. 3. The coefficient of determination (R^2) increased and CV-RMSEs decreased with additional angular information for all datasets (SPEC and BNC). Adding the data of a second angle as independent variables to the regression analyses is contributing most to R^2, thereafter as more directional information is added as smaller becomes the increase of R^2. For instance R^2 augmented for the dataset SPEC by 15 %, 8 % and 5 % by adding data of a second, third and fourth view angle, respectively.

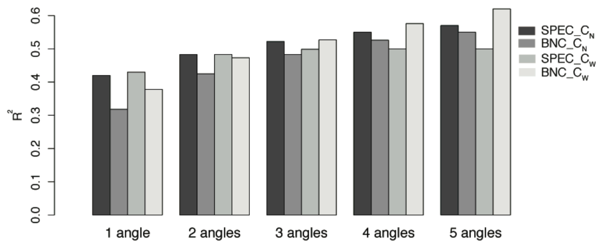


Figure 3. The coefficient of determination (R^2) augmented as more CHRIS view angles were involved in regression analyses. All models consisted of four independent variables.

Evaluating the contribution of directional information by spectral datasets (SPEC, BNC) revealed interesting differences. Models generated from untransformed reflectance values (SPEC) performed best for C_N in terms of R^2. For C_W, however, transformed data (BNC) with three or more angles involved performed better than SPEC.

3.2. Viewing Angle Combinations for C_N and C_W estimation

R^2 values and CV-RMSEs from models developed on data of all angular combinations (n = 31) were compared to discover which viewing angle combinations are promising to improve C_N and C_W estimates. This was done for all four datasets. We start reporting the results of monodirectional and continue then with multiangular models for C_N.

Best results were achieved with monodirectional models based on data of the nominal -36° angle for SPEC and BNC and poorest outcomes were derived from models developed on nadir (SPEC) or +36° data (BNC), as can be seen in Fig. 4. For multi-angle models the combination of off-nadir angles yielded the highest training R^2 values. We obtained maximum R^2 values with data of two viewing zenith angles (-/+36°) for BNC (training R^2 = 0.55), whereas SPEC (0.57) needed data of three viewing zenith angles (nominal -/+36° and +55°). Adding data of more than three angles as independent variables to subset selection did not improve the coefficients of determination any further. The algorithm simply selected the same CHRIS wavebands again as for the two or three-angle models.

We used two different reflectance datasets (SPEC, and BNC) to assess whether bidirectional effects are still present after continuum removal. For one-angle models, R^2 varied more for models based on continuum-removed than for untransformed data for both biochemicals (Fig. 4). Additionally, we observed that SPEC performed particularly well for models developed on data of one and two viewing angles compared to the transformed datasets. Turning to water content, in Fig. 4 it can be seen that the models developed on SPEC showed small variation regarding R^2. The maximum value of 0.5 was already achieved with the nadir model. However, the models based on BNC showed more variation in the outcomes. Maximum R^2 (0.62) was reached with a three-angle model (nadir/+36°/-55°).

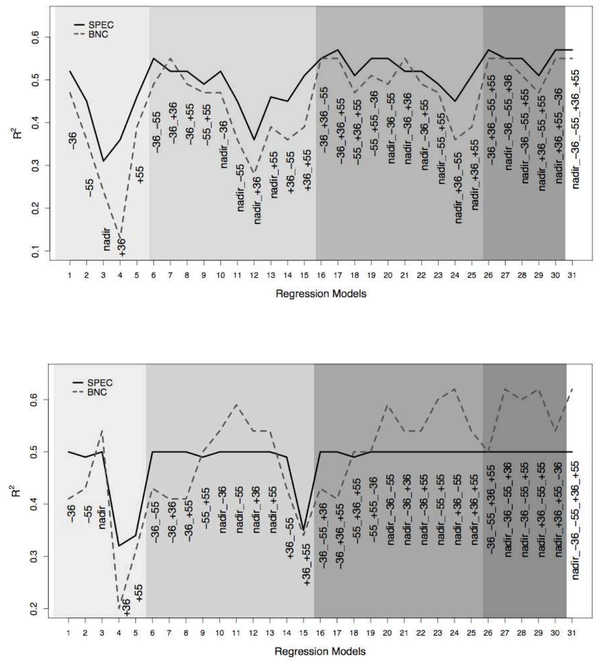
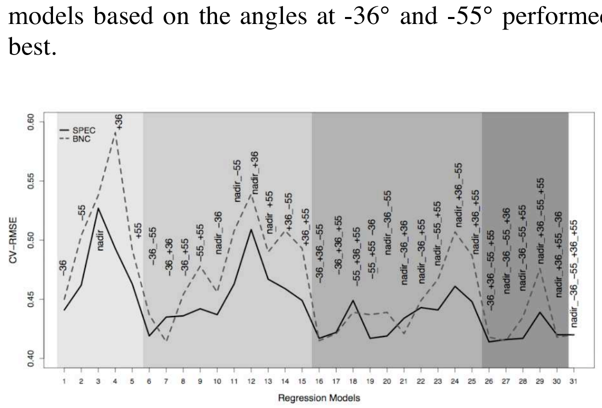


Figure 4. Coefficients of determination (R^2) of C_N (upper) and C_W (lower) regressed on 31 view angle combinations of SPEC and BNC. The background colors indicate the number of view angles provided as independent variables to the regression analyses.

Cross-validation revealed that CV-RMSEs and percentage relative errors tend to be smaller with increasing number of view angles involved (Fig. 5). For the dataset SPEC, CV- RMSEs ranged from 0.414 to 0.527 % dry weight C_N and relative errors varied between 20.3 and 26.5 %. If we consider both cross-validated measures (CV-RMSE and relative errors) the models based on the angles at -36° and -55° performed best.



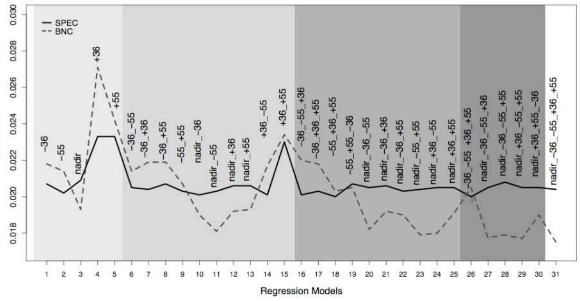


Figure 5. Cross-validated root mean square errors (CV-RMSE) of four-term models estimating nitrogen concentration (upper) and water content (lower). The x-axis indicates the evaluated 31 models and the background colors represent the number of angles involved in regression modeling.

The CV-RMSE is around 20 % lower compared to the monodirectional nadir model. However, for the BNC dataset the combination of backward and forward scattering viewing directions achieved lowest RMSEs. For BNC the combination of -/+36° data (CV-RMSE 0.414–0.419) was most promising. We observed larger range of CV-RMSEs for transformed datasets than for SPEC. For all datasets CV-RMSEs of the best model dropped more than 20 % compared to the nadir model.

4. DISCUSSION AND CONCLUSIONS

In general, monodirectional models trained on backward scattering data achieved higher R^2 values than those developed on data of the forward scattering direction. The finding that most information is contained in backward scattering viewing direction reflectance is consistent with other research which found an increase in bidirectional reflectance in the backward scattering direction in boreal forests but lower reflectance in forward scattering direction, due to a combination of gap and backshadow effects [28, 29]. These effects are more pronounced at high sun zenith angles and are emphasized in high absorbing spectral ranges such as the red band due to the lack of multiple scattering in this wavelength range. The monodirectional models developed on -36° data performed best for SPEC. The minimum reflectance corresponds with the forward scattering direction because the sensor views the non illuminated, shadowed leaf surfaces [29]. This is in agreement with our findings, where models based on data of the +36° and +55° angles obtained poor results for C_W. However, for C_N, models developed on data of the +55° angle performed similar to -55° models. In this viewing perspective, the sensor's field of view is still dominated by foliar material and the shadows seem to be less influencing than possible soil background effects, as seen from nadir. For C_N estimation nadir view direction played a minor role possibly due to shaded background that has strongest influences on the signal for small viewing zenith angles [30]. The large portion of gaps observed in this direction decreases the portion of leaf material seen from the sensor and thus the reflectance values. What is surprising is that this was not the case for C_W estimation where single-angle models based on nadir data performed best.

Another interesting finding was that C_W models developed on the dataset SPEC had very stable R^2 values (around 0.5) encompassing all angular combinations (except +36°/+55°) and a contribution to R^2 with additional angular data was not observable. It is difficult to explain this result, but it might be related to the sensor's spectral coverage (442–1019 nm) so that no major liquid water absorption feature could be used in this study. The original reflectance data might not be sufficiently sensitive to changes in water content in the weaker absorption feature at 970 nm. However, for the transformed datasets we obtained much more variability in R^2 values.

To assess the presence of directional effects after applying spectral transformation methods we compared the regression results of the continuum-removed dataset BNC with the results of untransformed reflectance values (SPEC). For single-angle models R^2 values varied considerably for both biochemical constituents between viewing angles, indicating that the normalization procedure did not remove all extraneous effects. For C_N, however, we observed that SPEC performed particularly well for models developed on data based on one or two viewing zenith angles. This indicates that untransformed spectral data contains more additional information related to e.g. tree structures, which possibly improved the regression models. Only starting from three view angles onwards, models developed using continuum-removed datasets improved due to contributing information from additional viewing angles, thus finally yielding higher R^2 values than SPEC.

This study has investigated the contribution of directional CHRIS data to the estimation of canopy C_N and C_W by assessing R^2 values and CV-RMSEs of regression model fits between the chemical constituents and 31 angular combinations of four spectral datasets. It was shown that 1) directional data impoved regression models for C_N and C_W estimation and lowered cross-validated RMSEs, 2) SPEC performed better than BNC for monodorectional models, 3) in general monodirectional models developed on the backward scattering viewing directions were superior to models based on forward scattering data, 4) integrating data of more than three viewing angles did not improve regression models any further and 5) models based I combinations of off-nadir data performed best for C_N but not for C_W.

The results of this study demonstrate that not only the assessment of structural vegetation parameters profit from additional information contained in directional reflectance data but also biochemical estimates. These findings support the potential of multiangular Earth observations for ecological monitoring and modeling studies.

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